Spontaneous Symmetry Breaking in Rotating Convection within a Thin Spherical Shell

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Are planets symmetric?

Recent observations provided new insights into latitudinal temperature structure of Uranus's atmosphere. Notably, the brightness temperature is higher at Uranus's northern polar region compared to its equatorial region[1]. This intriguing anomaly contrasts with gas giants like Jupiter[2, 3] and Saturn[4, 5] where temperatures of two polar regions are relatively symmetric and do not differ much from their equators.

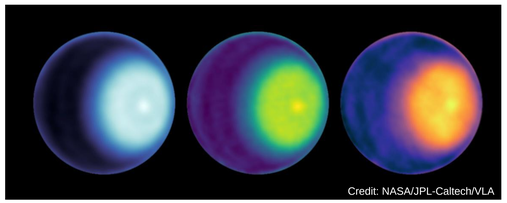


Fig. 1. Microwave observations of Uranus' Northern hemisphere and polar region.

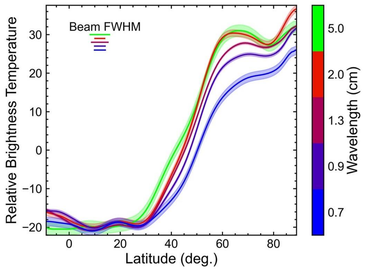
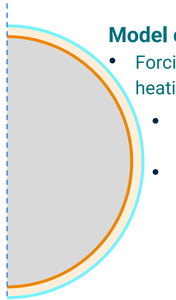


Fig. 2. Uranus's Latitudinal trends in brightness temperature for different observation wavelengths.

- Deep atmospheres of giant planets should be less influenced by solar radiation.
- **Q1: Why does Uranus's northern polar region have a much higher brightness temperature compared to its equatorial region?**
- **Q2: Is the other polar region of Uranus a symmetrical counterpart of its northern polar region?**

3D Atmosphere General Circulation Model

We explored a **new scenario** where the atmospheric dynamical processes under **symmetric forcing** can lead to a **spontaneous hemispheric asymmetry**.



Model configuration

- Forcing: Uniform bottom heating and top cooling flux
  - Rayleigh-Benard-type convection
  - Planetary rotation

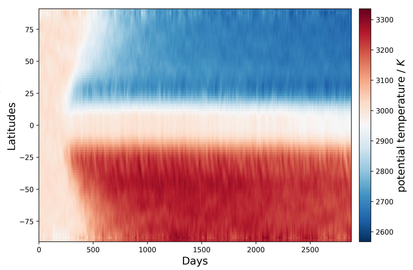


Fig. 3. Time series of zonal-mean potential temperature of a horizontal atmosphere layer.

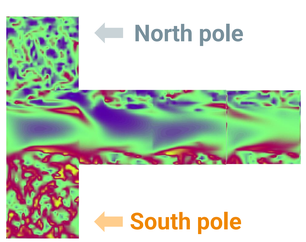


Fig. 4. Potential temperature simulated using a cubed-sphere GCM.

Starting from adiabatic atmosphere profile, symmetry breaking begins at mid-latitude regions and propagates to high-latitudes

- One hemisphere **warm**, the other hemisphere **cool**
- Which hemisphere is warm is random across identical repeated simulations.

Atmosphere Zonal Profile

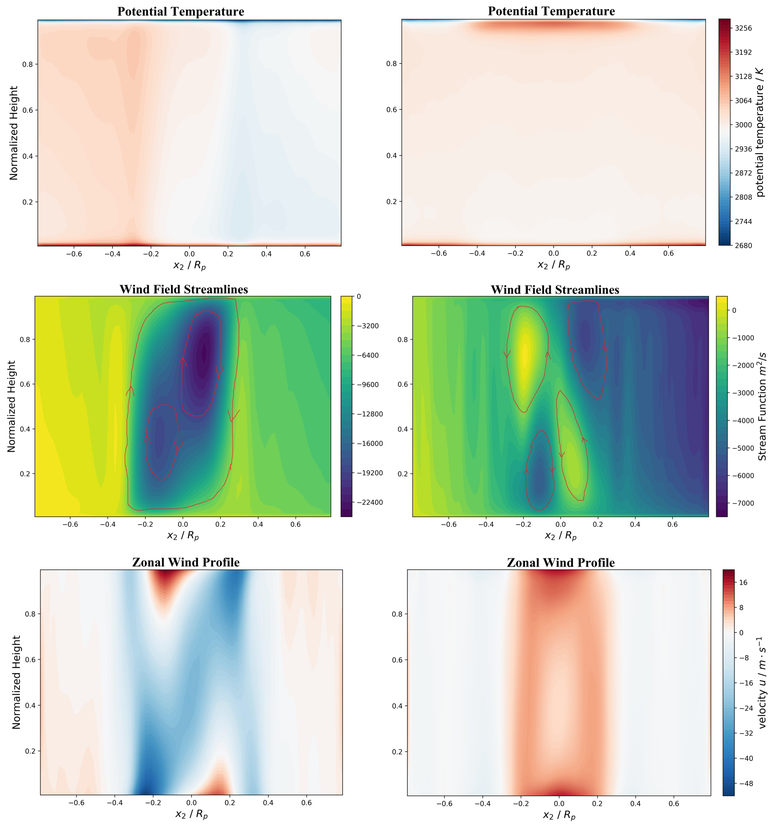


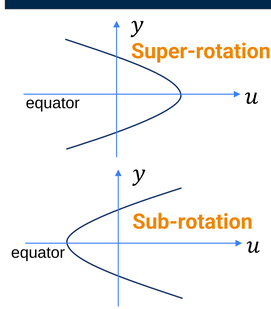
Fig. 5. Asymmetric

- Potential temperature manifests asymmetry between N-S hemispheres.
- A large-scale circulation over equatorial region segregates two hemispheres.
- **Sub-rotation** at equatorial region in the mid-level altitude

Fig. 6. Symmetric

- Symmetric potential temperature about the equator.
- Symmetric circulation cells on both sides of the equator.
- **Super-rotation** at equatorial region

Vorticity Analysis



Hemisphere	ζ_r	f	$\zeta_a = \zeta_r + f$
North	> 0	> 0	> 0
South	< 0	< 0	< 0

North	< 0	> 0	≈ 0
South	> 0	< 0	≈ 0

Fig. 7. Schematic diagram of zonal wind profile with respect to the latitude in super-rotation and sub-rotation scenarios.

For **equatorial sub-rotation**, there will be a **wide latitude band across the equator** where the **absolute vorticity is very close to 0.**
However, the scenario of equatorial super-rotation does not have such feature.

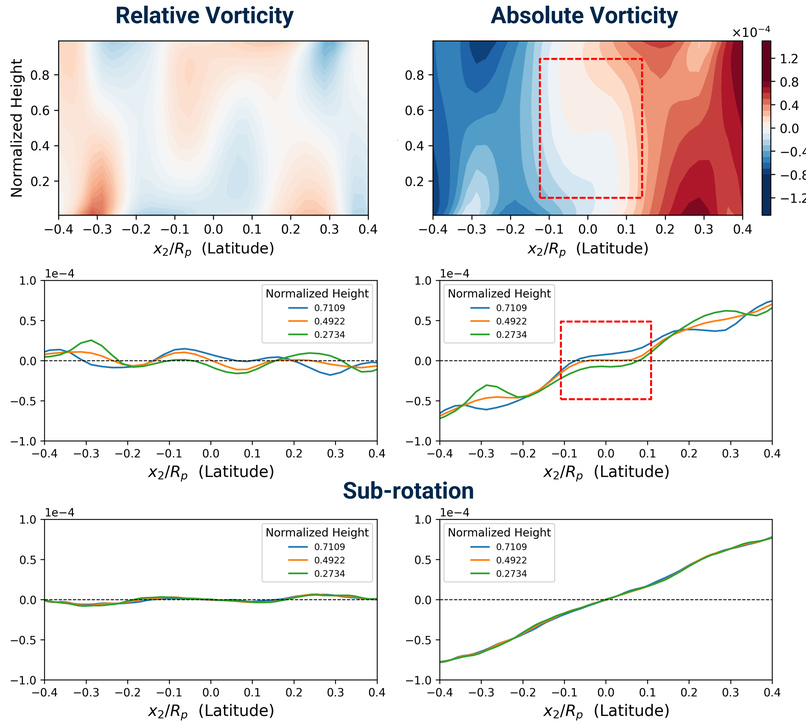


Fig. 8. Relative vorticity and absolute vorticity near the equatorial region for sub-rotating and super-rotating jet streams.

The zero vorticity zone (red dashed square) at equator will prevent any perturbation with a spatial scale smaller than it from moving to the other hemisphere.

Key Takeaways

- Atmospheric dynamical processes under symmetric forcing can lead to a spontaneous temperature asymmetry in northern and southern hemispheres.
- Equatorial sub-rotation could contribute to North-South asymmetry, while super-rotation does not have such effect.
- Uranus may have constant summer and winter hemispheres regardless of which side is facing the Sun.

References

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